ASSIGNMENT-3 SOLUTION

Subject Name & Code:

Physics- BE01000021

LASER

1) List out and explain the properties of laser.

Answer:

Laser light is fundamentally different from ordinary light due to the following key properties:

1. **Coherence:**
   - **Explanation:** This is the most important property. The light waves in a laser beam are in phase with each other in both time and space. This means the crests and troughs of all the waves align perfectly.
   - **Types:**
     - **Temporal Coherence:** A measure of the correlation between the phases of a light wave at different points along the direction of propagation. It is related to the monochromaticity of the light. Lasers have high temporal coherence, meaning they can maintain a constant phase relationship over a long distance.
     - **Spatial Coherence:** A measure of the correlation between the phases of a light wave at different points transverse to the direction of propagation. This allows a laser beam to be focused to a very tight spot.
2. **Monochromaticity:**
   - **Explanation:** Laser light consists of a single color, meaning it has an extremely narrow range of wavelengths (or frequencies). Ordinary white light is a mixture of all visible wavelengths.
   - **Reason:** This occurs because stimulated emission produces photons that are identical to the incident photon, resulting in light of a very specific energy and wavelength.
3. **Directionality:**
   - **Explanation:** A laser beam is highly directional and has a very small divergence angle. It propagates as an almost parallel beam, unlike ordinary light which spreads out in all directions.
   - **Benefit:** This allows laser light to be transmitted over long distances with little spread and to be focused onto a very small area with high intensity.

4. **High Intensity/Brightness:**
   - **Explanation:** Because the laser beam is directional and coherent, its energy is concentrated in a very small region. Even a low-power laser can have a much higher intensity (power per unit area) than a conventional light source of much higher power because conventional light spreads out in all directions.

2) Explain with neat diagram of the process of absorption of light, spontaneous emission and stimulated emission of light.

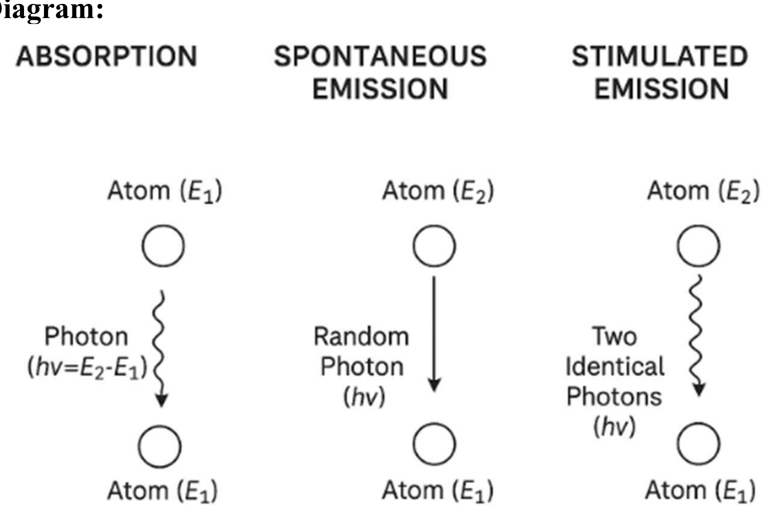
Answer:

These three processes are the fundamental interactions between light (photons) and matter (atoms).

- **Absorption:**
  - An atom in a lower energy state (E_1) absorbs an incoming photon of energy exactly equal to the difference between a higher energy state and its current state (E_2 - E_1).
  - The photon is destroyed, and the atom is excited to the higher energy state (E_2).

- **Spontaneous Emission:**
  - An atom in an excited energy state (E_2) is unstable. Without any external influence, it will spontaneously decay to a lower energy state (E_1) after a short, random time interval.
  - It emits a photon with energy $hv = E_2 - E_1$. The photon is emitted in a random direction and has a random phase.

- **Stimulated Emission:**
  - This is the core process behind laser action. An incoming photon of energy $hv = E_2 - E_1$ *stimulates* an atom already in the excited state (E_2) to decay to the lower state (E_1).
  - The result is the emission of a second photon that is **identical** to the incident photon in every way: same energy, phase, polarization, and direction of travel.
  - This process produces coherent and amplified light.
  - **Diagram:**



3) What are Einstein's coefficients? Explain them.

Answer:

To describe the probabilities of the three processes above, Albert Einstein introduced three coefficients:

1. **Einstein Coefficient for Absorption (B_{12}):**
   - It is a measure of the probability that an atom in a lower energy state E_1 will absorb a photon and transition to a higher energy state E_2 per unit time per unit energy density of the radiation field.
2. **Einstein Coefficient for Spontaneous Emission (A_{21}):**
   - It is a measure of the probability that an atom in a higher energy state E_2 will undergo spontaneous emission and transition to a lower energy state E_1 per unit time. It is independent of the external radiation field.
3. **Einstein Coefficient for Stimulated Emission (B_{21}):**
   - It is a measure of the probability that an atom in a higher energy state E_2 will be stimulated by an existing photon to emit a second identical photon and transition to E_1 per unit time per unit energy density of the radiation field.

4) State the necessary conditions for stimulated emission and explain the Einstein's A and B coefficient. Derive the relation between Einstein's A and B coefficients.

Answer:

- **Necessary Condition for Stimulated Emission:** The fundamental condition is **Population Inversion** (explained in detail in Q5). There must be more atoms in the higher energy state (E_2) than in the lower energy state (E_1). Under normal conditions, the opposite is true (Boltzmann distribution), and absorption dominates.
- **Explanation of A and B Coefficients:** (As explained in Q3 above).
- **Derivation of Relation between A_{21} and B_{21}:**
  Consider two energy states E_1 and E_2 ($E_2 > E_1$) of an atom in a cavity at thermal equilibrium with temperature T. Let N_1 and N_2 be the number of atoms in states E_1 and E_2 respectively. Let u(v) be the energy density of radiation of frequency $v = (E_2 - E_1)/h$.

At equilibrium, the rate of absorption must equal the rate of emission.
   - **Rate of Absorption:** $R\_abs = N_1 * B_{12} * u(v)$
   - **Rate of Emission:** $R\_emi = N_2 * A_{21} + N_2 * B_{21} * u(v)$ (Spontaneous + Stimulated)

At equilibrium: R_abs = R_emi

$$=> N_1 * B_{12} * u(v) = N_2 * A_{21} + N_2 * B_{21} * u(v) \quad ...(1)$$

According to Boltzmann's distribution, the population ratio is:

$$N_2 / N_1 = \exp[-(E_2 - E_1)/kT] = \exp(-hv/kT) \quad ...(2)$$

Rearranging equation (1) for u(v):

$u(v) [N_1B_{12} - N_2B_{21}] = N_2 A_{21}$

$\Rightarrow u(v) = (N_2 A_{21}) / (N_1B_{12} - N_2B_{21}) = (A_{21}) / ((N_1/N_2)B_{12} - B_{21})$

Substituting from (2): $N_1/N_2 = \exp(hv/kT)$

$\Rightarrow u(v) = A_{21} / [B_{12} \exp(hv/kT) - B_{21}]$ ...(3)

Planck's law of blackbody radiation gives the energy density for the same cavity:

$u(v) = (8\pi hv^3 / c^3) * 1 / [\exp(hv/kT) - 1]$ ...(4)

For equations (3) and (4) to be identical for all values of temperature T, the coefficients must be related. Comparing the two equations:

- The -1 in the denominator of (4) must come from the $- B_{21}$ in the denominator of (3). This implies that the coefficients for absorption and stimulated emission must be equal: $B_{12} = B_{21}$
- The constants in front must also be equal. Therefore: $A_{21} / B_{21} = (8\pi hv^3) / c^3$

This is the crucial relation between Einstein's A and B coefficients. It shows that the probability of spontaneous emission (A_{21}) is proportional to the cube of the frequency, meaning it is much more significant for higher energy transitions (e.g., X-rays) than for lower energy ones.

5) What is population inversion? Explain the necessity of population inversion for lasing action.

Answer:

- **Population Inversion:** It is a non-equilibrium state where the number of atoms in a higher energy state (N_2) is *greater* than the number of atoms in a lower energy state (N_1). This is the opposite of the normal Boltzmann distribution ($N_1 > N_2$).
- **Necessity for Lasing Action:** For light amplification to occur, **Stimulated Emission must dominate over Absorption**.
  - If $N_1 > N_2$ (normal state), when light passes through the medium, absorption ($N_1 \rightarrow E_2$) will be more probable than stimulated emission ($N_2 \rightarrow E_1$). The light will be attenuated, not amplified.
  - If $N_2 > N_1$ (population inversion), stimulated emission becomes more probable than absorption. When a photon of the correct energy passes through, it is more likely to trigger the emission of an identical photon from an excited atom than to be absorbed by a ground-state atom. This leads to a **chain reaction** of identical photon production, resulting in the **amplification** of light. Achieving population inversion is the first essential step in creating a laser.

6) What is meant by pumping? Discuss in brief Optical pumping.

Answer:

- **Pumping:** The process of supplying energy to the laser medium (atoms, molecules, etc.) to achieve the necessary non-equilibrium state of **population inversion** is called pumping. It is the method of exciting atoms from the lower energy level to a higher energy level.
- **Optical Pumping:** This was the first method used (e.g., in Ruby laser). It involves using a bright external light source (e.g., a flash lamp or another laser) to irradiate the laser medium. Atoms in the ground state absorb photons from this light and are excited to higher energy levels. The light source must provide photons with energies corresponding to the absorption bands of the laser medium. It is a simple method but often inefficient as much of the light energy is wasted as heat.

7) Explain the working of a resonant cavity and its role in laser operation.

Answer:

The laser resonant cavity (or optical cavity) is typically formed by placing two mirrors facing each other at either end of the laser medium (the "gain medium"). One mirror is fully reflective (100%), and the other is partially transparent (e.g., 99%) to allow the laser beam to exit.

- **Working and Role:**
  1. **Sustaining Amplification:** Photons emitted through stimulated emission travel along the axis of the cavity. They bounce back and forth between the two mirrors.
  2. **Passing Through the Medium:** Each time these photons pass through the gain medium, they stimulate more excited atoms to emit identical photons. This causes an exponential growth in the number of coherent photons inside the cavity—a process called **gain**.
  3. **Forming a Coherent Beam:** Only light waves that are perfectly aligned with the cavity axis (i.e., traveling perpendicular to the mirrors) will be reflected back and forth multiple times and be amplified. Waves traveling at other angles will quickly leave the sides of the cavity and be lost. This ensures the **directionality** of the laser beam.
  4. **Output Coupling:** The partially transparent mirror (output coupler) allows a fraction of this intense, coherent, and directional beam to escape, which is the useful laser beam we use.

In essence, the resonant cavity provides **positive feedback** to sustain the lasing action and defines the **spatial coherence** and **direction** of the output beam.

8) Explain the production of lasers by Ruby Crystal.

Answer:

The Ruby laser, built by Theodore Maiman in 1960, was the first working laser.

- **Active Medium:** A synthetic ruby crystal rod (Al_2O_3 doped with ~0.05% Cr^{3+} ions). The chromium ions provide the necessary energy levels.
- **Pumping Mechanism: Optical Pumping** using a high-intensity helical flash lamp surrounding the ruby rod.
- **Energy Level Diagram (3-level system):**
  1. The flash lamp excites Cr^{3+} ions from the ground state E_1 to a broad band of higher energy levels E_3.
  2. The ions in E_3 are unstable and rapidly undergo non-radiative transition (releasing heat) to a metastable state E_2. This transition does not involve light

emission.

3. The metastable state E_2 has a long lifetime (~3 ms). This allows a large number of ions to accumulate here, leading to **population inversion** between E_2 and E_1.

4. Spontaneous emission of a few photons triggers **stimulated emission** from E_2 to E_1, producing photons of wavelength 694.3 nm (deep red light).

- **Cavity:** The ends of the ruby rod are silvered to act as the resonant cavity mirrors.

- **Output:** The laser emits a pulsed output (not continuous) because the lower laser level E_1 is the ground state. It is very difficult to maintain population inversion as more than half of the atoms must be excited from the ground state.

9) Explain the construction and working of He-Ne (Helium-Neon) laser with the help of energy level diagram.

Answer:

The He-Ne laser is a common continuous-wave (CW) gas laser.

- **Construction:**
  1. **Active Medium:** A mixture of Helium and Neon gas (typical ratio 10:1) inside a sealed glass tube at low pressure.
  2. **Pumping Mechanism: Electrical Pumping**. A high DC voltage is applied between a cathode and an anode at the ends of the tube, causing a glow discharge (like a neon sign).
  3. **Cavity:** Two mirrors are mounted externally (Brewster's windows are used on the tube ends to avoid reflective losses and achieve polarized output) or internally. One mirror is fully reflective, the other is ~99% reflective.
- **Working and Energy Level Diagram (4-level system):**
  1. **Energy Transfer:** Energetic electrons from the electrical discharge collide with and excite Helium atoms to metastable states (2^1S_0 and 2^3S_1).
  2. **Resonant Transfer:** The excited He atoms (He*) collide with ground-state Neon (Ne) atoms. The energy levels of He* are very close to the 5s and 4s energy levels of Ne. This allows for highly efficient **resonant energy transfer**, exciting the Ne atoms to the 5s and 4s states. (He* + Ne(ground) -> He(ground) + Ne*). This is the key step to achieving population inversion in Ne.
  3. **Population Inversion:** The 5s and 4s levels of Ne are metastable and become densely populated. The lower laser levels (4p and 3p) are normally empty and have very short lifetimes. Thus, a strong population inversion is easily created between the 5s->4p and 3s->3p transitions.
  4. **Stimulated Emission & Lasing:** Stimulated emission occurs from the Ne 5s level to the 4p level (wavelength 632.8 nm, red light – the most common He-Ne line) and from the 4s level to the 3p level (wavelength 3.39 µm, IR). The photons produced stimulate further emission.
  5. **Fast Depopulation:** The Ne atoms in the lower laser levels (4p, 3p) quickly decay non-radiatively to the 1s level, and then through collisions with the tube walls to the ground state. This fast depopulation prevents a bottleneck and allows the population inversion to be maintained continuously.

10) List the applications of laser light.

Answer:

- **Scientific:** Spectroscopy, Interferometry (LIGO for gravitational waves), Holography.
- **Medical:** Surgery (scalpels, eye surgery), Dentistry, Skin treatments, Cancer therapy.
- **Industrial:** Cutting, Welding, Drilling, Marking, Engraving, Lithography, 3D Scanning (LiDAR).
- **Commercial:** Bar code scanners, Laser printers, Optical communications (fibre optics).
- **Military:** Range finding, Target designation, Guidance systems, Defence systems.
- **Everyday Use:** DVD/Blu-ray players, Laser pointers, Light shows.

11) List the application of laser in industry.

Answer:

- **Material Processing:**
  - **Laser Cutting:** Precise cutting of metals, plastics, fabrics, and composites with a narrow kerf and high speed.
  - **Laser Welding:** High-precision, deep-penetration welding for automotive and aerospace components.
  - **Laser Drilling:** Creating very fine, precise holes in materials like turbine blades.
  - **Laser Marking and Engraving:** Permanently marking serial numbers, barcodes, and logos on metals, plastics, and ceramics.
- **Additive Manufacturing:** 3D printing technologies like Selective Laser Sintering (SLS) and Stereolithography (SLA) use lasers to fuse powder or cure resin layer by layer.
- **Metrology and Alignment:** Laser interferometers measure distances with extreme accuracy. Lasers are used for precise alignment in construction (e.g., laser levels).
- **Communications:** Fibre optic communication uses laser diodes to transmit vast amounts of data over long distances.

12) List the applications of laser in medical.

Answer:

- **Surgery:**
  - **Ophthalmology:** LASIK and PRK for vision correction, retinal surgery.
  - **Dermatology:** Removal of tattoos, birthmarks, scars, and hair. Skin resurfacing.
  - **Dentistry:** Drilling and shaping teeth, treating gum disease.

- **General Surgery:** Used as a "laser scalpel" for bloodless surgery due to its ability to cauterize as it cuts (e.g., tumor removal).

- **Diagnostics:** Optical coherence tomography (OCT) for high-resolution imaging of the retina and coronary arteries.
- **Therapy:** Low-level laser therapy (LLLT) for pain relief, reducing inflammation, and promoting tissue repair.
- **Cancer Treatment:** Photodynamic Therapy (PDT), where a laser activates a drug to destroy cancer cells.

13) Why does spontaneous emission dominate over stimulated emission at normal temperature?

Answer:

At normal temperature and thermal equilibrium, two key factors cause spontaneous emission to dominate:

1. **No Population Inversion:** The Boltzmann distribution dictates that the population of the lower energy level (N_1) is always vastly greater than the population of the higher energy level (N_2), i.e., $N_2 << N_1$. Since stimulated emission requires $N_2 > N_1$ to dominate, it is suppressed.
2. **Weak Radiation Field:** Stimulated emission depends on the presence of an existing photon in the radiation field ($u(\nu)$) to trigger the process. At normal temperatures, this ambient thermal radiation field is extremely weak. Spontaneous emission, however, is an intrinsic process that does not require any external trigger and occurs randomly regardless of the radiation field.

In short: The combination of an extremely small N_2 and an extremely weak $u(\nu)$ makes the rate of stimulated emission negligible, while spontaneous emission proceeds unaffected.

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